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A model-based assessment of the impact of revitalised R&D investments on the European power sector

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ABSTRACT

This paper presents an analysis of the effect of enhanced research and development (R&D) efforts for a set of low-carbon power technologies on the development of the European energy sector. It applies a methodology using the concept of Two-Factor-Learning, which quantitatively links trends in technology cost to both accumulated R&D investments and production volumes. The impacts of the latter on the energy sector are then simulated in a consistent manner with the POLES global energy model. On this basis, it compares the total system costs of an assumed increase in worldwide R&D investments that for the EU are in line with proposals made in its European Strategic Energy Technology Plan to a baseline development. It finds that an increase in research efforts at a global level will contribute to reducing the costs of currently less mature low-carbon technologies, thus accelerating their market entry. When comparing two scenarios that both fulfil the EU's 2020 energy and climate objectives and differing only in their R&D investment levels, the reduced technology costs allow EU support policies for renewables and carbon values to be reduced, and the cumulative (discounted) benefit of the accelerated research efforts is positive in the long term.

Contents

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1. Introduction

In order to limit the effect of climate change, the international community of states agreed on the necessity of deep cuts in global greenhouse gas emissions [1]. The European Union (EU) is committed to a significant contribution to these worldwide efforts, and hence set a firm independent target to reduce EU greenhouse gases by at least 20% by 2020 compared to the level of 1990. This will be extended to 30% provided that a comprehensive international agreement broadens global participation and obliges other developed countries to commit themselves to comparable emission reductions [2,3]. For the long-term (2050), emission reductions in the order of 80–95% are envisaged for developed countries as a group. Given that energy production and consumption remain the largest source of GHG emissions in the EU, its Member States have adopted ambitious policies that aim at reducing energy demand and decreasing the carbon intensity of energy supply.

There is wide acknowledgement on the need for innovative low-carbon technologies in order to realise the emission cuts required in the energy sector [4,5]. To this end, the EU adopted an Energy Policy for Europe [2,6] with an integrated energy and climate package (overview in [7]). The package includes a 20% renewable energy target for the year 2020 [8], a 20% increase in overall energy efficiency [9] and the deployment of new technologies for carbon reduction [10]. Moreover, it amended the European Emission Trading Scheme [11,12] that provides economic incentives for the reduction of GHG emissions for sectors covered under this instrument.

These policies are complemented by 'technology-push' policies that foster research and development. The European Strategic Energy Technology Plan (SET-Plan) [13] aims at supporting Research and Development (R&D) and the market uptake of low-carbon energy technologies. In the context of its implementation, the European Commission estimated the additional volume of R&D funding needed for implementing the SET-Plan [14].

In the present article, we analyse the impact of increasing global R&D levels in line with these needs identified for Europe. The methodology applied is based on the concept of the Two-Factor-Learning Curve (TFLC), according to which technology costs for power generation technologies are reduced through both learning and researching. This concept is then used to quantitatively analyse the benefits of the increase in R&D funding on the energy sector, employing the global energy model POLES in an adapted version. The methodology is explained further in Section 2 of this paper together with the energy model applied.

Two scenarios have then been set up, a *reference scenario* and a *Global R&D scenario*, which differ in the assumptions made for global and European RD&D investments in wind energy, photovoltaic and concentrating solar energy use, bioelectricity and carbon sequestration technologies. In order to assess whether the research boost can help the EU in realising its energy sector policy targets at lower costs, in both scenarios the European renewable energy and climate change objectives set for 2020 are met. By fixing the quantities – i.e. the level of greenhouse gas emissions and the share of renewables in final energy demand–the savings in terms of a reduced electricity price (including the support scheme to renewables) and a lower CO_2 value can be compared to the additional R&D investments. Section 3 introduces these scenarios and Section 4 discusses results before we conclude in Section 5.

2. Methodology

The basic underlying concept used for estimating the impact of RD&D investments on technological improvements, and hence the energy sector, is the Two-Factor-Learning Curve. It establishes a relationship between the unit production costs of a technology and the cumulative production levels ('learning-by-doing') and cumulative knowledge stock ('learning-by-searching') as described in Section 2.1.

From an operational viewpoint, learning effects were implemented through a multi-step approach, combining a spreadsheet model for technology learning and a partial equilibrium model of the energy sector (POLES; see Section 2.2).

Due to the lack of a comprehensive database on corporate and public R&D investments by technology, historic R&D investments had to be approximated in order to calibrate the TFLC. This methodology is laid out in Section 2.3.

2.1. The Two-Factor-Learning approach

The concept of learning has first been described by Wright [15] to describe the cost reductions observed in airplane production. It explains an observed relationship between improvements in performance and productivity of a technology and the accumulation of experience. In a traditional one-factor-learning curve this is approximated by plotting a reduction in technology costs against the accumulated installed capacity [16–18].

This one-factor-learning aggregates several elements of 'learning' (overview in [19,20]), whose disaggregation can be useful in some cases. Two of the most important steps are learning by doing [21] and learning by researching [22]. Learning by doing refers to the relationship between unit production costs and learning effects due to the accumulation of experience in the manufacturing process (in the energy sector often approximated by the installed capacity). The relationship between an accumulated knowledge stock and production costs is defined as the learning by researching effect. Combining the effects of learning by doing and learning by researching leads to a Two-Factor-Learning Curve [23]. Such a learning curve can be described as follows for a given technology t and time period y [19,24]:

$$C_{t,y} = n \cdot Q_{t,y}^{-\alpha} \cdot KS_{t,y}^{-\beta} \tag{1}$$

with C = overnight installation costs, €/kW; Q = cumulative installation, kW; KS = knowledge stock (here: approximated through cumulative R&D investments, €); α = elasticity of learning by doing; β = elasticity of learning by researching; n = normalisation parameter with respect to initial conditions; t = technology; y = period (year).

The knowledge stock is approximated here as the depreciated cumulative historical global R&D investments with a time lag. Depreciation is introduced as proposed by Klaassen et al. [24] in order to take account for the fact that past knowledge gradually becomes less relevant. The depreciation rate of historic R&D investments is set at 3% per annum [25]. Uncertainties associated with the depreciation rate are considered to be of limited relevance due to much of the cumulative R&D investment being realised in more recent years. The time lag introduced – here assumed to be two years – reflects the delay between research investments and the production of tangible results. Whereas for research of more basic nature this time lag may be considered as short, it is confirmed not only by econometric analyses [25,26] but further motivated by the fact that the technologies considered here can rely on the existence of a considerable research infrastructure that can absorb additional R&D investments with limited delays.

The parameter n is calculated by applying Eq. (1) for the initial point of the learning curve, i.e. using cost of production ($C_{t,0}$), cumulative production ($Q_{t,0}$) and knowledge stock ($KS_{t,0}$) for the initial year 0. The parameters α and β in the Eq. (1) are the learning elasticities. The so-called learning rates are derived on the learning elasticities and relate to the cost reduction after each doubling of capacity or knowledge stock, respectively.

$$\text{Learning rate}_{\text{learning by doing}} = 1 - 2^{-\alpha} \tag{2}$$

$$\text{Learning rate}_{\text{learning by researching}} = 1 - 2^{-\beta} \quad (3)$$

Whereas the concept of one factor learning curve (OFLC) is well established and learning rates are available from a variety of sources and have become well acknowledged (see e.g. [5]), there is much less information on TFLCs. Kahouli-Brahmi [19] lists around 60 learning-by doing rates for various energy technologies referring to the OFLC-concept, compared to less than 20 each for the learning-by-doing and learning-by-researching of the TFLC.[2]

2.2. Implementation

Due the limited availability of reliable two factor learning rates for the technologies considered here, a Two Factor Learning Curve Spreadsheet model (TFLC model) was developed to parameterise a TFLC employing available parameters of a OFLC complemented with historic data on technology costs, the proxy for knowledge stock (i.e. cumulative public and private R&D investments) and the cumulative installed capacity. Based on this information the model computes a one factor learning curve and then decouples it into a two factor learning curve, determining the two factor learning elasticities (α, β). This is further calibrated for the time horizon until 2030 via successive iteration with the POLES model, using 'business-as-usual' assumptions on the evolution of public and corporate R&D investments as foreseen in the reference scenario.

The calibrated TFLC is then used to calculate the technology cost developments for the more ambitious R&D investment profile defined in the '*Global R&D*' scenario. As changes in technology cost have an impact on the future installed capacities of a given technology, several iterations between the TFCL model and the POLES model are executed until convergence is reached, i.e. until the marginal changes caused by any additional iteration become very small.

POLES (Prospective Outlook for the Long term Energy System) is a global sectoral simulation model for the development of energy scenarios until 2050. POLES has been developed and applied in a variety of EU projects, e.g. the WETO, WETO-H2, TRIAS, HOP! and GRP project [4,27–30]. For the present work, the model has been slightly adapted in order to better capture the R&D effects. For example, the possibility of reflecting market-pull mechanisms for CCS has been introduced and a number of technology pathways have been adapted to the techno-economic characteristics published in European Commission's Information System of the SET-Plan [31].

The dynamics of the POLES model corresponds to a recursive simulation process, in which energy demand and supply in each national/regional module respond with different lag structures to international price variations in the preceding periods. In each module, behavioural equations take into account the combination of price effects and of techno-economic constraints, time lags or trends.

The world is subdivided into 47 regions in the POLES version that has been used for this work. For each region/country POLES articulates four main modules dealing with:

- Final energy demand by main sectors;
- New and renewable energy technologies;
- The electricity, conventional energy and transformation system;
- Primary energy supply.

This structure allows for the simulation of a complete energy balance for each region, from which import demand/export capacities are estimated. At the same time the horizontal integration is ensured in the energy markets module of which the main inputs are the import demands and export capacities of the different regions.

In the final energy demand module, the consumption of energy is divided into 11 different sectors. Each of these sectors belongs to one of the three 'blocks': Industry, Transport and Residential-Tertiary-Agriculture. For each sector, the energy consumption is calculated separately for substitutable technologies and for electricity, taking into account specific energy consumptions.

POLES contains technologically detailed modules for energy-intensive sectors, including power generation, production of iron and steel, aluminium and cement, as well as modal transportation sectors. All energy prices are determined endogenously in POLES.

2.3. Estimation of historical R&D investments

Information on public R&D investments is mainly based on the IEA Energy Technology RD&D Statistics Service.[3] Even though the database contains no data for some EU Member States, it is considered the most complete source available for public energy R&D investments disaggregated by technology. Apart from the European members, the database includes the large energy R&D funders USA and Japan, but does not include China. Note that data gaps make it difficult to assess the trend of R&D investments over time and to directly compare between Member States. This is due to changes in the methodology of reporting in some countries such as France, the geographical coverage, differences in the scope of relevant R&D allocated to energy; the extent to which regional data are captured and the inclusion of institutional funding [32].

On top of the national public R&D investments, funds through the various European Research Framework Programmes have been taken into account. A detailed assessment of FP6 is taken from [30], while for FP7 only some provisional figures of the first call have been analysed. Data from previous research framework programmes are taken from a variety of resources, including [33] for PV, [34] for wind energy, [35] for CCS under FP5, [36] for CSP. For bioenergy as well as for other low-carbon technologies, estimates of FP5 EC funding are provided by [37].

Unlike for public R&D, there is no single database available that provides technologically disaggregated information on corporate R&D investment in a consistent manner. Industrial R&D investments have therefore been estimated based on the combination of several approaches depending on the type of basic information available (Table 1). To this end, the turnover of the energy equipment manufacturing industry was approximated by multiplying the specific investment cost in a given year by the annual installed capacity in the same year. The corporate R&D investments were assumed to be a proportion (R&D intensity) of the industry turnover in a given year. The R&D intensities are taken from an in-depth analysis of European R&D investments in low-carbon energy technologies for the year 2007 [32]. In the case of CCS, a similar approach could not be followed due to the lack of turnover in the burgeoning industry. Instead, corporate investments are taken from information provided by the Zero Emission Technology Platform [38].

2.4. Economic assessment

The economic impact of accelerating research efforts on certain technologies in the power sector is approximated by comparing the additional R&D investments with the benefits to the sector in

[2] He found low learning-by-doing rates in the order of 2–4% prevail for mature technologies such as coal, oil, and lignite-based power production. For new renewable energy technologies, such as PV power production, learning by doing rates in the order of 10–20% are reported. The ranges for learning by researching rates are around 10–15% for wind energy, photovoltaics, hydropower and gas combined cycle turbines.

[3] A publicly accessible database on energy R&D budgets from the IEA member countries, based on data that are collected from government funders.

Table 1
Estimated corporate and public R&D investment in the EU and at OECD level.

Technology	R&D investments in EU 2007 (bn €$_{2008}$)		Cumulative R&D investment 1974–2007 (bn €$_{2008}$)			
			EU		Global*	
	Public	Corporate	Public	Corporate	Public	Corporate
Wind energy	0.092	0.29	2.2	2.2	3.6	3.6
Photovoltaics	0.163	0.22	3.2	0.6	7.2	1.2
Concentrating solar power	0.038	0.05	0.9	0.2	2.6	1.1
Bioelectricity	0.211	0.06	2.1	1.4	4.7	3.9
CCS	0.056	0.24	0.25	0.7	0.54	1.6

Source: IEA RD&D statistics and [30].
Notes: Data are very rough approximations only and shall be used only for the purpose of the present analysis.
Figures from the IEA have been complemented by relevant investments under the EU Research Framework programmes. In the case of bioelectricity, figures are approximated by considering the 'total bioenergy' R&D investments minus those parts related to transport biofuels instead of using figures from the subcategory 'applications for heat and electricity'. A focus on the latter would suffer from a substantial lack of data at that level of detail.
* IEA Member Countries only.

form of reduced electricity production costs. The latter are affected by the change in technology costs between the scenarios, which imply that the European energy and climate change objectives can be met at different levels of renewable energy support schemes and different CO_2 prices.

The economic impact of the measure is given by comparing the change in benefits and in costs between the two scenarios.

$$\text{Economic impact} = \Delta\text{benefits} - \Delta\text{costs} \quad (4)$$

$$\Delta\text{Benefits} = \Delta\text{Electricity production costs} \quad (5)$$

$$\Delta\text{Costs} = \Delta\text{R\&D investments}_{\text{corporate}} + \Delta\text{R\&D investments}_{\text{public}} \quad (6)$$

3. Definition of scenarios

In order to single out the effect of boosting R&D efforts on the costs of reaching EU energy and climate targets, the analysis rests on the assumption that both the share of renewable energies and levels of greenhouse gas emissions are identical across the scenarios in the EU-27 by 2020. Otherwise, the change in greenhouse gas emission levels and the share of renewables would need to have been put into monetary terms.

The scenarios therefore differ only in the exogenous assumptions on R&D investments into low-carbon power technologies. Apart from this, they both build on the iTREN-2030[4] integrated scenario,

- that incorporates the effects of the recent economic crisis;
- which assumes the EU greenhouse gas reduction target of 20% below 1990 for 2020 will not only be reached, but even be over–fulfilled;
- that meets the European target of a 20% share of renewables in final energy demand. In line with the trends assumed for the EU, an active renewable energy and climate change policy has been assumed to be implemented also in many other world regions in the reference scenario, following [4];
- in which the oil price remains at high levels with almost 100 €$_{2008}$/bbl in 2020 and around 108 €$_{2008}$/bbl in 2030.

Under these assumptions, European total energy demand will be close to 2005 levels by 2030.[5] The stabilisation of energy consumption is aided by a significant decoupling of transport energy demand and GDP growth. The economic crisis also greatly affects industrial activities and therefore lowers the final energy demand of industry, while the residential and service sector are expected to further increase their energy consumption. Unlike for final energy consumption, the demand for electricity will continue to rise in all sectors, following a development similar to previous years. On the supply side, the energy sector in general, and the power sector in particular, strongly react to the rising carbon dioxide price and the renewable energy policy support by substituting carbon-intensive fuels with low-carbon alternatives. Renewable energies reach a share of 20% in final energy demand.[6]

The combination of stagnating energy demand and decreasing carbon intensity of power generation leads to substantial reductions in greenhouse gas emissions both compared to a baseline and 1990 levels. By 2020, European emissions of greenhouse gases are 24% below the emissions in 1990 in line with the targets set for the scenario. They fall further to be 29% below 1990 levels by 2030. Much of the emission reductions are realised in the power sector and households. At global level, greenhouse gas emissions increase further until 2020 before they also start to decrease. By 2030, global emissions are 14% above their level in 2005.

Starting from these market framework conditions two scenarios have been constructed that differ in their level of R&D investments by technology over the period 2010–2020, resulting in different developments of investment costs and deployment, hence allowing by comparison the assessment of additional research and development investments.

3.1. Reference scenario

In the reference scenario annual R&D investments in the period 2010–2020 are assumed to remain at a level equal to the public investments in 2007. This may be considered as a rather conservative assumption, in particular when bearing in mind recent support to energy technologies in the context of recovery packages to mitigate the impact of the economic crisis.

Because R&D intensities are assumed to remain constant, corporate R&D investments develop in line with the net sales of the industries. R&D intensities for wind (2.6%) and photovoltaic (2.5%) are derived from the corporate R&D investments found for EU-based companies in [32] while for other sectors they have been

[4] This scenario has been developed in the context of the FP6 research project iTREN-2030. A key task of iTREN-2030 was to generate a consistent reference development until 2030 that integrates and harmonizes technological developments on the energy and transport side, energy prices and economic trends with demand for energy and transport and their environmental impacts [39].

[5] For a discussion on the evolution of the energy sector under the iTREN-2030 scenario assumptions see [40].

[6] The actual share of renewables in final energy consumption was set at around 18.7% instead of 20%, as the POLES model in its current version does not consider some emerging technology option. In a comparison between renewable energy scenarios done with the POLES and the GreenX models, it was found that these missing categories account for 1.2–1.3% of renewables in final demand by 2020 [41].

set at 2.5%. In computational terms, the corporate R&D investment is derived for the EU and the rest of the world based on the turnover, which is determined by the projected investment cost and the annual deployment in each region, following the same procedure as for estimating the historical R&D investments.

3.2. Global R&D scenario

The additional R&D investment has been defined so that for the EU, it corresponds to the research needs identified in the SET-Plan Communication on 'Investing in the development of Low Carbon Technologies for the EU' [14]. At the same time, equivalent R&D efforts are assumed to be pursued at the global level in a coordinated and harmonised manner. This is an optimistic assumption, which is nevertheless backed by calls from G8 leaders and a recommendation to the G8 for the 'development of a G20 Strategic Energy Technology Plan [42], modelled on the European example'. Beyond 2020, it is assumed that the investment level in the *Global R&D scenario* is the same as in the reference case, capturing the effect up to 2030 of the additional R&D investments made during the period 2010–2020.

In operational terms, the additional R&D investments under the *Global R&D scenario* have been determined using a four-step iterative approach (which is described in more detail in [43]). The sectoral/technological R&D needs as identified by the SET-Plan are taken as a starting point [44], and are compared to current research activity levels in order to identify the gap. However, not all of today's research activities focus on the objectives pointed out in the various roadmaps; hence only a fraction of present R&D investments would contribute to their financial needs. This fraction of existing investments is estimated to range between 50% and 70%. In a next step, a simplified allocation of the total R&D needs to public and industrial funders has been performed, using the year-2007 ratio of public–private R&D funding for each technology based on [32]. On this basis, and assuming a constant ratio of public–private efforts, the corporate R&D intensities for EU-based companies are deduced. In the final step, these R&D intensities are applied to the turnover of the global industry. The public R&D investment is then estimated assuming the same distribution of public and private efforts as for the EU.

This leads to an assumed cumulative R&D investment in the technologies considered here of 61 bn € at a global level in the *Global SET-Plan* scenario on top of the efforts under the reference scenario, of which 15 bn € are for the EU (see Table 2).

On top of this, a dedicated demonstration scheme for CCS is assumed in the *Global R&D scenario*, addressing the part of the production costs that stem from carbon capturing process for some demonstration plants. This demonstration scheme is capped at 10 bn € for the EU. At the global level, similar efforts are made in line with the roadmap developed by the IEA.[7]

4. Results

4.1. Impact on technology costs

Following the logic of Two-Factor-Learning, the higher levels of cumulative R&D investments in the *Global R&D scenario* result in lower technology costs than in the reference scenario. This is reinforced by higher learning-by-doing effects due to the additional deployment of the now cheaper technologies. Note that significant reductions in technology costs already occur in the reference scenario. The additional technology cost reductions that are initiated by the strengthened R&D efforts in the *Global R&D scenario* are depicted in Table 3.

The two-factor learning curve parameters, as described in Section 3 and calculated in this study, are shown in Table 4. A 're-constructed' one-factor learning rate is also included corresponding to the investment cost evolution determined for the *Global R&D scenario* for comparison purposes with ranges reported in the literature (e.g. [5,19,46,47]).

4.2. Impact on the energy sector

As mentioned, the share of renewables and the level of greenhouse gas emissions in the EU are the same in the reference and *Global R&D scenarios* by 2020. This implies that changes to the EU energy sector in terms of demand and supply are limited until 2020 by construction.

Even though renewable energies must achieve the same share in the European final energy demand by 2020 in both scenarios, the enhanced competitiveness of selected renewable energy power generation technologies leads to a slightly higher share of renewables in gross electricity consumption than in the reference scenario as expected. This is achieved despite the fact that overall electricity demand increases slightly (+0.1% by 2020) because of the rebound effect in the *Global R&D scenario* compared to the reference case. Changes in the electricity price result from the reduction in the European CO_2 price and the specific renewable energy premium tariffs which in return bring about lower electricity prices when they are passed through to the consumer.

In both scenarios, hydropower, wind energy and biomass-based electricity generation account for more than 90% of the total renewable electricity production in the EU by 2020. In spite of this general picture prevailing across both scenarios, the *Global R&D scenario* shows a mild shift towards more innovative renewable energy technologies by 2020. In particular CSP, wind offshore, PV and biomass gasification experience a positive R&D effect (see Fig. 1). The counter-intuitive effect of (slightly) lower biomass thermal electricity production capacities is due to the fact that this technology hardly reduces its investment costs under the assumption of higher R&D investments, and thus becomes less competitive under the regime of reduced renewable energy premiums compared to other renewable energy technologies. On the global level, where – unlike in the EU – the deployment of renewable energies is not

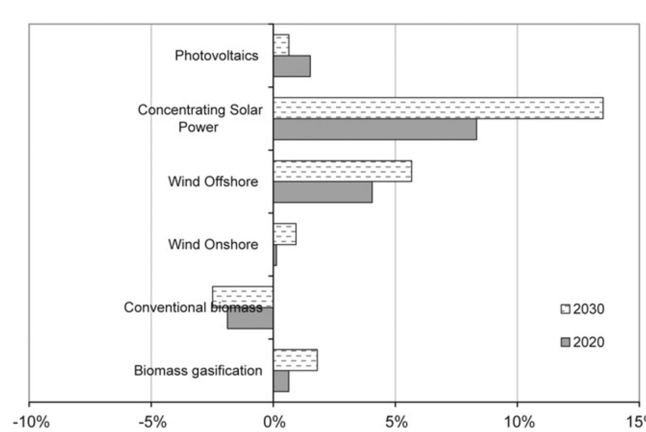

Fig. 1. Changes in EU installed capacities in the *Global R&D scenario* relative to the reference scenario in 2020 and 2030.

[7] The IEA roadmap [45] proposes that 'OECD governments increase funding for CCS demonstration to achieve an average annual investment of 3.5 bn USD to 4 bn USD from 2010 to 2020'. At the same time there should be an 'annual investment for CCS of 1.5 bn USD to 2.5 bn USD from 2010 to 2020 in non-OECD regions via the establishment of new financing strategies'. Over the ten-year period 2010–2020 this would amount to 50–65 bn USD. We assume the lower value at an exchange rate of 1.25 USD = 1 €. Subtracting from the global amount the investments considered for the EU (10 bn €) leads to the assumption of 30 bn € to be invested in the rest of the world.

Table 2
Assumed R&D investments under the *Global R&D scenario* additional to the reference scenario in period 2010–2020.

Global R&D scenario [bn €$_{2008}$]	EU			World without EU		
	Corporate	Public	Total	Corporate	Public	Total
Wind energy	2.0	1.0	3.0	5.5	4.5	10.0
Photovoltaics	4.0	3.0	7.0	7.5	7.0	14.5
Concentrating solar power	1.0	0.5	1.5	7.0	6.0	13.0
Bioelectricity	0.4	0.1	0.5	2.0	1.0	3.0
CCS	2.5	0.5	3.0	4.5	1.0	5.5
Total	9.9	5.1	15.0	26.5	19.5	46.0

Table 3
Investment cost evolution in the reference and *Global R&D scenarios* up to 2030.

	Investment cost in reference scenario [€$_{2008}$/kW]			Global R&D: additional cost reduction compared to the reference scenario	
	2007	2020	2030	2020	2030
Wind onshore	1150	1000	950	5%	2%
Wind offshore	2500	1400	1300	9%	4%
Photovoltaics	3900	1700	1350	13%	9%
Concentrated solar power	5900	3150	3050	11%	10%
Conventional thermal bioelectricity	2800	2300	2000	0%	0%
Bioelectricity – gasification	4800	2200	1800	7%	2%
Coal with CCS	–	2300	2150	8%	7%
Combined-cycle gas turbine with CCS	–	1250	1100	8%	7%

capped by default, the effect of increasing R&D efforts becomes more visible. By 2030, the overall installed renewable energy capacity in the power sector increases by 1.5% compared to the reference scenario.

The introduction of Carbon Capture and Storage strongly depends on the construction of a number of demonstration plants. The *Global R&D scenario* assumes the construction of up to 12 demonstration plants in the EU starting from 2015, following the Technology Roadmap for CCS. Under the assumption of additional R&D efforts of 3.5 bn € and another 10 bn € dedicated to market introduction, CCS plants enter the market some 5–10 years earlier than in the reference scenario. Hence, by 2015 as much as 1.7 GW is installed in the *Global R&D scenario* in the EU, four times the quantities projected in the reference scenario even though the carbon price is higher in the latter. By 2020, the effect from the additional efforts assumed under the *Global R&D scenario* widens the gap. The installed CCS capacities reach 5.5 GW in the EU, well in line with the IEA Blue Map Scenario [45]. Due to the accelerated deployment of CCS plants in the *Global R&D scenario*, by 2030 GHG emissions in the power sector are almost 1% below the reference scenario in the EU.

At the global level, 25 GW of demonstration plants equipped with CCS are installed compared to 9 GW in the reference scenario by 2020 (Fig. 2). This is triggered by the efforts to scale up CCS assumed in the *Global R&D scenario* that reach some 30 bn € in world regions other than the EU in line with the IEA who called for almost 100 CCS demonstration plants [45]. Together with the higher share of renewables at the global level, the accelerated market introduction of CCS could lead to additional emission reductions of 1.4% in the power sector by 2030 worldwide.

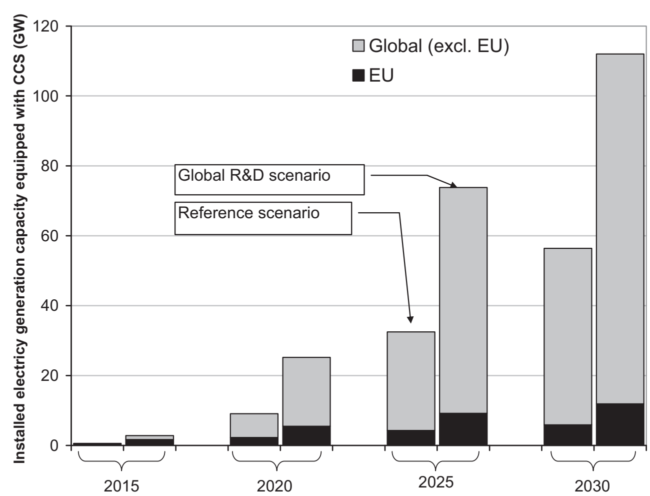

Fig. 2. Impact of a research and deployment support to the uptake of CCS.

Table 4
Learning rates for the scenarios and related experience curves.

	Reference scenario			
	OFLC learning rate	*Global R&D scenario*		
		Two-factor learning curve		One-factor learning curve learning rate
		Learning-by-doing rate	Learning-by-researching rate	
Wind onshore	7.0%	3.0%	10.0%	9.5%
Wind offshore	7.5%	2.0%	10.0%	10.5%
Photovoltaics	20.0%	18.0%	9.5%	25.0%
Concentrating solar power	7.5%	5.0%	10.0%	10.5%
Bioelectricity – conventional	12.5%	7.0%	11.5%	12.5%
Bioelectricity – gasification	12.5%	3.5%	11.5%	14.0%
CCS	2.0%	1.0%	10.0%	3.5%

4.3. Economic assessment

Due to the lower technology costs in the *Global R&D scenario*, the support schemes for renewables and the carbon price are reduced compared to the reference scenario. By 2020 the European CO_2 price that is in line with achieving the same GHG emission levels would be 1.1 €$_{2008}$/tCO_2 lower than the reference scenario value. At the same time, the renewable energy premium tariff per kWh is also reduced, even though in total terms the faster market uptake of more innovative, more expensive renewable energies means that the absolute amount of the renewable energy support remains about constant. As a consequence, electricity production costs are slightly reduced (up to 1%) in the *Global R&D scenario*, whereas additional costs occur due to higher R&D investment levels.

In total, net costs occur in the *Global R&D scenario* in the first years caused by the additional R&D investments that are needed as from 2010 onwards, while their benefits in terms of reduced electricity production costs materialise in the later periods. The (discounted at a rate of 3%) cumulative net benefit becomes positive around 2020. By 2030, it reaches 13.6 bn €$_{2008}$. The internal rate of return (IRR) of the changes triggered by the additional R&D investments modelled in the *Global R&D scenario* is some 15% when considering the period 2010–2030. In order to also capture the benefits beyond 2030 to the extent possible, the assessment has been extended to the year 2040.[8] Taking this longer time frame into consideration, the IRR increases to 16%.

Further benefits are realised under a *Global R&D scenario* which are not fully captured in the present analysis. Addressing them quantitatively in a systematic manner would require a general, multisectoral macroeconomic approach, which lies outside of the scope of the present work.

These benefits include

- lower electricity and CO_2 prices in the economy as a whole;
- lower CO_2 prices for carbon-intensive sectors. For example in the industrial sector the reduction in the CO_2 price means a saving of around 0.5 bn €$_{2008}$ in 2020 and 0.4 bn €$_{2008}$ by 2030.[9]

Furthermore, it should be stressed that the research efforts considered to be undertaken within the *Global R&D scenario* are viewed by the sectors as crucial to ensure the availability of and help in improving the technical maturity and competitiveness of low-carbon technologies that will form the backbone of the future power system when striving for higher greenhouse gas emission reductions in line with a 2 degree target pathway. Hence, the differences between the reference case and *Global R&D scenario* in terms of technological availability and maturity could be more pronounced than those considered in the context of this exercise.

4.4. Discussion of uncertainties

The analysis is exposed to a number of uncertainties, involving those related to the methodology, parameters, data, and set-up of scenarios.

From a methodological viewpoint, establishing a quantified relationship between R&D inputs and technology improvements as done in the Two-Factor-Learning Curve is difficult due to knowledge spillover effects from other sectors, time lags and the uncertain and non-linear nature of research inputs and outputs, in particular when considering breakthrough innovations.

Furthermore, existing data on R&D investments and available learning-by-researching coefficients often carry a high uncertainty. The learning rates can differ significantly for the same data sets across various approaches [48] (see for a comprehensive discussion with further references [20]); even negative cost improvements were found (e.g. [49] for wind turbines; [50] for CCGT). Also, the learning by doing and learning by researching effects are linked. They act as a virtuous self-reinforcing cycle [26,51]. Overall, taking into account the problem of separating economies of scale from learning, of internal feedback between various ways of learning and technological and national spill-over effects, there is a risk that learning rates are overestimated.

Despite these constraints, some studies clearly demonstrate the validity of using Two-Factor Learning Curves to explain production costs [25,52] reinforcing its utility for the present paper while acknowledging related uncertainties.

Additional uncertainties arise when applying this concept to assess future trends in technology costs [20]. These are related to the fact that learning rates may decrease at a higher maturity of the technology ([49,50], see the example of coal in [19]), that the total decrease in costs is limited (which can be avoided by introducing floor costs in modelling) and that reinforcing effects are over-estimated. Nevertheless, the TFLC has been applied in models and provided reasonable results such as in [53], who derive R&D levels to give a least cost pathway for improvements in investment costs, in effect an optimum R&D schedule. The present approach, which combines a spreadsheet model on learning with the POLES model instead of relying on endogenous learning in POLES, allowed close monitoring of the learning effects in order to minimise the above uncertainties.

The limited availability of consistent datasets means that elevated uncertainties are also associated with the estimation of cumulative historic R&D investments. These become even more pronounced when assuming future trends for the developments in R&D investments of the different scenarios. Moreover, the approximation of the knowledge stock by the cumulative R&D investments disregards improvements in the efficiency that research is being performed. It could be imagined that a research-intense scenario would be accompanied by measures to increase the efficiency of research, through e.g. the exploitation of synergies between key actors.

Finally, the scenario assumptions are simplified. In particular the assumptions on the trends in future R&D investments by technology under a baseline and an accelerated framework carry significant uncertainties. Whereas for the EU the assumptions are broadly in line with the proposals related to the SET-Plan, the related global assumptions may be considered as too optimistic.

5. Conclusions

The analysis demonstrates that an ambitious global increase in research efforts can reduce the investment costs of the low-carbon power technologies by in-between 4% and 13% compared to reference trends. This in return fosters their market penetration. In general, the less mature technologies such as offshore wind energy, PV, CSP and biomass gasification benefit over proportionally.

Technologies to capture and store CO_2 emissions are deployed faster under the conditions of the *Global R&D scenario*, bringing forward their large-scale market entry by at least five years. However, this is not only due to rising research efforts, but in particular also to the assumed simultaneous introduction of a market pull incentive for CCS.

The possible reductions in the carbon prices and levels of renewable energy support can, in the longer run, outweigh the additional

[8] Macro-economic assumptions beyond 2030 could not be taken from the iTREN-2030 project; instead, they are adapted from [4]. However, the trends in the techno-economic characteristics of power technologies are extended until 2040 in line with the learning rates described before.

[9] This may be considered as a conservative estimation as only emissions of CO_2 and not those of other GHG are considered.

R&D investments. Considering a time horizon between 2010 and 2030, the internal rate of return (IRR) of an R&D push in line with the SET-Plan is in the order of 15% in the EU. The cumulative benefit of the measure is negative in early years before turning positive around the year 2020 and remaining so thereafter. Note that the analysis neglects additional positive side effects to consumers and industry such as cost reductions in other sectors due to the lower CO_2 prices. At the same time, however, the analysis builds on a number of optimistic assumptions.

Due to the poor availability of data on R&D investments and methodological constraints, the results of the present assessment are associated with elevated uncertainties. Both the methodology and the underlying data basis would need to be further developed and improved to better capture the R&D effects in future work. Nonetheless, the present results provide a first indication of the trends initiated by SET-Plan-like efforts and therefore are considered valuable information for decision-making despite the associated uncertainties.

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